Kalina & Organic Rankine Cycles: How to Choose the Best Expansion Turbine?

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1. General Presentation

1.1 Cryostar in figures

- **350 employees**
- **145 Million € turnover in FY 2006**
- **90% export**
- **15 Million € investments in 2005-07**
- **Part of the new**

Boil-Off gas reliquefaction unit

Skid mounted HC turboexpanders

High pressure reciprocating pump
Recognised as worldwide experts in the following areas:

- **Industrial gases**
  No.1 in the application of cryogenic and industrial gas pump sectors

- **Oil & Gas**
  One major supplier of turbo-expander/compressors in oil & gas treatment (HC dewpointing, ethylene plants)

- **LNG carriers**
  No.1 in « boil-off » gas handling and recovery (90% market share)

- **Energy recovery**
  Principal supplier of energy recovery expanders for « geo-pressure » application on natural gas grids (30 MW installed in Europe in the last 20 years plus North America ongoing)
1. General Presentation

1.3 Cryostar new markets

- **Geothermal and heat recovery expansion turbines**

- **In construction:** one TG500 delivering ca 3.3 MWelec for Siemens Kalina cycle in Unterhaching (Bavaria/Germany)
- **Ongoing project:** other TG500 for Siemens Kalina cycle in Offenbach/Bellheim
- **Pre-selected for Soultz Hot Dry Rock ORC Project**
- **Pre-selected for Innamincka Kalina Project**
2. Radial Turbines For Binary Cycles

2.1 Radial inflow turbine

★ Main elements:

1. A high pressure barrel from which the gas first expands through guide vane arrangement that is located in the circumference of the wheel.

2. The gas is accelerated in the guide vanes and enters the turbine wheel. It converts the kinetic portion of energy contained in the gas by means of deflection into mechanical energy.

3. The gas leaves the wheel axially at the low pressure level and is passing afterwards through the discharge diffuser where velocities are reduced to normal pipeline velocities.

4. The power generated by the wheel is given to a shaft which runs in high speed bearings. This power can be recovered by driving a compressor or a generator.
The expander wheel must be designed at optimum ratio of blade tip speed and spouting velocity: \[ \frac{U}{C_0} \]

- \( U \) = tip speed (m/s)
  - rotating speed of the blades at the furthest extremity from the rotating axe

- \( C_0 \) = spouting velocity (m/s)
  - the magnitude of the absolute velocity vector at nozzle exit under isentropic conditions (i.e., no losses in the nozzle passage)

\[ C_0 = \sqrt{2000 \cdot \Delta H_i} \]

- \( \Delta H_i \) = Isentropic enthalpy drop (kJ/kg)

\( U/C_0 \) is a measure of the shape of the velocity triangle in the inter-space between nozzle exit and rotor inlet.
The expander wheel must be designed at optimum specific speed $N_s$

$N_s = \text{specific speed}$

Links main sizing variables: flow, speed, head

$N_s$ is shape factor for the passage of the wheel

$$N_s = \frac{76. N}{1000} \sqrt[3]{\frac{Q_{\text{out}}}{\Delta H_{\text{is}}}}$$

Specific Speed

with:

- $\Delta H_{\text{is}}$ Isentropic enthalpy drop (kJ/kg)
- $N$ Wheel speed (rpm)
- $Q_{\text{out}}$ Vol. Flow Rate (m$^3$/s)

Low $N_s$ at design point

High $N_s$ at design point
2. Radial Turbines For Binary Cycles  
2.2 Expander wheel design

☆ Designing for the best efficiency

Optimum Ns for known process data

Calculation of angular velocity

\[ \omega = \frac{(N_s)_{\text{optimum}} \cdot \sqrt{Q_{\text{out}}}}{\Delta h_{\text{is}}^{3/4}} \]

\( \omega \) too high?

Yes → Decrease \( Q_{\text{exit}} \)

No → Optimum wheel speed

Optimum U/C0

C0 given by process data

Calculation of tip (wheel) speed

\[ U_{\text{tip}} = \left( \frac{U}{C_0} \right)_{\text{optimum}} \times C_0 \]

\( U_{\text{tip}} \) too high?

Yes → Decrease C0

No → Optimum wheel diameter

\[ d_{\text{tip}} = \frac{2}{\omega} \cdot \left( \frac{U}{C_0} \right)_{\text{optimum}} \cdot \sqrt{2 \cdot \Delta h_{\text{is}}} \]
Expander limitations:

Circumferential (Tip) wheel speed

Depending on material Ti alloy > Al 7 Series > Stainless Steel

Depending on wheel type (open or closed)

Depending on shaft connection type (Hirth or Polygon)

Speed corresponding to max Tensile and Yield stresses admissible related to wheel geometry
2. Radial Turbines For Binary Cycles  2.2 Expander wheel design

★ Expander limitations:

Power Density

Usually expressed in Horse Power per Square Inch [hp/in²]

Defined the load admissible per unit of wheel surface area

Depending on material:

Ti alloy > Stainless Steel > Al 7 Series
★ Expander limitations:

**Bearing (sliding speed) speed**

Most of the time, tilting pad (also called Michell) bearings are used.

Maximum sliding speed defined by bearing manufacturer.
2.2 Expander wheel design

★ Expander limitations:

Sound velocity or Mach Number

At wheel discharge, Ma = 1 causes shock

At throat of the guide vanes, flow is limited to Ma = 1

Further downstream, Ma > 1 can give flow distortion, a cause for loss on efficiency
2. Radial Turbines For Binary Cycles

2.2 Expander wheel design

★ **Expander limitations:**

**Application to turboexpanders for binary cycle**

★ **Most of the time Titanium alloy wheels must be used because of:**
   - Inlet Temperature higher than 100-120 degC
   - “Aggressive” working fluid like ammonia-water mixture

★ **Consequently it gives higher margin for:**
   - Wheel tip speed
   - Power Density

★ **... so higher efficiency**

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**Kalina cycle**

84.31%-w NH₃, 5.47 kg/s, pout = 7.4 bara

![Graph showing Isentropic Efficiency vs Pressure Ratio for Kalina cycle](image-url)
2. Radial Turbines For Binary Cycles

2.3 Designing for best efficiency

Operating range for Cryostar binary cycle expanders

Kalina Cycle - Offenbach (design for summer)

ORC with iC4-Soultz High Brine Flow

ORC with iC4-iC5 Waste heat recovery

Experience shows that efficiency decreases when:

- Pressure ratio increases
- % liquid at outlet of expander increases

Expander efficiency of Turboexpander-Generators (TG) at design points

TG for binary cycles: 0.82 < efficiency < 0.9
2. Radial Turbines For Binary Cycles

2.3 Designing for best efficiency

**Up to 200°C inlet temperature**
**Up to 12 MWelec**

radial inflow turbines for binary cycles are ...

...*Standard machines for CRYOSTAR*

Installed base:

- More than 1600 turbo-expanders & -compressors in operation
- *ca* 150 TG machines generating more than 80 MW electricity
2. Radial Turbines For Binary Cycles  

2.3 Designing for best efficiency

★ TG machines

TG300/60 delivering 4MWe
Challenge: Sealing gas for closed cycle.

Role of the seal gas:
- prevent contamination of process gas by the lubricant
- Limit or eliminate gas leakage around the shaft

Kalina cycle:
- Use of process fluid impossible: NH₃/H₂O leads to liquid formation and corrosion problems;
- Inert Nitrogen is often chosen;
- Needs to limit the flow of N₂ which is lost afterwards;
- «Dry Gas Seal» system;
- Little losses of process gas unavoidable.

ORC cycle:
- Use of ORC fluid possible: clean & dry iC₄, iC₅, R134A... used as seal gas;
- Oil sealing system with drainer or Dry Gas Seal is used;
- Seal gas migrating into oil system is cleaned from oil (coalescing filter);
- Cleaned seal gas is recovered by recompression to inlet of condenser;
- No losses of the process gas.
Kalina cycle:  
**Dry Gas seal**

- **Need of external source of Nitrogen;**
- **Low flow is necessary 1-2 m3/h;**
- **Polluted N₂ by NH₃ & H₂O needs to be stored before treatment;**
- **Possibility to « wash » the NH₃ gas to recover in the storage tank.**
ORC cycle: Solution for sealing
*Oil seal + drainer + recompression*
3. ORC Cycle Optimisation

Ability to fit ORC process data and the expander at the same time
3. ORC Cycle Optimisation

★ **Goal:** expander frame size downsizing

For the same brine flow & temperature data:

- **Isopentane**
  - Expansion from 9 to 1.1 bara
  - Optimal machine TG700
  - Net Cycle Power = 2.1 MW

- **Isobutane**
  - Expansion from 35 to 3.6 bara
  - Optimal machine TG500
  - Net Cycle Power = 3.2 MW

- **Propane**
  - Expansion from 42 to 8.7 bara
  - Optimal machine TG300
  - Net Cycle Power = 3.5 MW
Radial inflow turbines for binary cycles are standard machines:

- **Flexible design with high efficiency**

Kalina & Organic Rankine Cycle:
how to choose the best expansion turbine?

Buy a Cryostar one !!!